ABSORBER-COUPLED SUPERCONDUCTING TRANSITION EDGE SENSORS FOR SUBMILLIMETER IMAGING

James A. Chervenak, Ross Henry, Tom Stiles, Alex Bier, Dominic Benford, R. Shafer, J. Staguhn, and S. H. Moseley
NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

Kent Irwin and Gene Hilton
National Institute of Standards and Technology, Boulder, CO 80303

ABSTRACT

We describe absorber-coupled superconducting transition edge sensor (TES) arrays for imaging detection of submillimeter wavelengths. We report on the design and fabrication of small linear detector arrays whose scaleable architecture enables filled focal planes arrays in large formats. The bolometer pixels consist of a micromachined SiN or Si membrane with a photolithographic superconducting thermometer on the membrane to monitor its temperature changes. Several superconducting bilayer fabrication techniques for Mo/Au and Mo/Cu have been evaluated for robustness and noise performance. An absorber layer of Bi/SiO is shadow-masked onto the linear arrays of detectors which exhibits low film stress and uniform absorption across the submillimeter band. The detectors show good noise performance, approaching the phonon noise limit for TES bolometers. We describe a detector bilayer design for suppressing excess noise in Mo-based TES sensors that showed an amplifier limited 1/f knee of 100 mHz.

INTRODUCTION

Applications for astrophysical measurements at submillimeter and millimeter wavelengths presently require increases in array size with state-of-the-art low-noise, high-speed sensors. Current measurement systems have succeeded in scaling to larger arrays (tens and hundreds of pixels) by the inherently limited method of individually instrumenting the bias and readout of each pixel. To enable future NASA missions like SAFIR or CMBPOL, a technical path to arrays with thousands of elements must be demonstrated. Detectors for these missions must be robust, stable, and exhibit uniformity over large arrays, and will likely also require improved noise performance.

One technology that has been identified to fill this need is superconducting transition edge sensor bolometers on micromachined focal planes. This technology has been demonstrated (with single pixels and small numbers of pixels) to exhibit low noise with suitable responsivity and dynamic range for submillimeter measurements [1,2]. It has also been demonstrated that transition edge sensors are integrable with multiplexed readout of superconducting quantum interference devices (SQUIDs), which can read out large format arrays of TESs without signal degradation [3]. Further, filled focal plane arrays in micromachined silicon have been realized in formats with hundreds of pixels (the SHARC II camera) [4] and proposals for increasing that pixel count are underway (the SCUBA II camera) [5].

Here we describe the fabrication of TES arrays for measurements at submillimeter wavelengths. Integration of these detectors with systems for astronomical light and cryogenic radiometry have been published previously. We have followed several recipes for bilayers proposed in the literature (Mo/Cu [6] and Mo/Au [7]) and show noise performance of the sensors when integrated into bolometers. We have pursued development of thin Bi layers as a submillimeter absorber [8] and shown that it has good characteristics for use as a broadband absorber on micromachined substrates.

Contact information for J.A.Chervenak : Email: jcherven@pop500.gsfc.nasa.gov phone (301) 286-9162

FABRICATION

We report the details of production of the linear arrays of transition edge sensor bolometers shown in Figure 1(a) and 1(b). These arrays consist of eight bolometers with 1 mm^2 SiN membranes. The SiN (or Si) membranes are fabricated by backetching away the frame silicon by either wet-etching in KOH or dry etching in a Deep Reactive Ion Etcher (DRIE) to yield the 2x10 mm^2 area on which the thermometer elements and leads are deposited. In the case of DRIE of SiN or Si and KOH of Si membranes a buried oxide etchstop a few hundred nm in thickness is required. This technique has also been demonstrated for manufacturing 32 pixel linear arrays [4]. DRIE with a 3000 Angstrom thick oxide etchstop shows good etch uniformity across a four inch wafer and has can occur late in the process to minimize handling of the membrane wafers. A wafer of membranes can be patterned for "punchthough" and then laser diced into chips. In the case of wet-etch of the frame silicon, we have membrane wafers prior to metallization steps so that KOH residue can be kept separate from the metals. Yield can be negatively affected by breakage during handling of the membrane wafers. Thermal isolation or punchthrough of the membranes is achieved by micromachining narrow legs (5 μm x .8 mm) in the .5 μm thick nitride membrane. The micromachined legs are designed to act as a torsion bar when flexed so that the frame (seen at the top and bottom of Figs 1(a) and 1(b)) can be folded out of the plane leaving only the linear array of membranes to fill the focal plane. Close-packed 2D filled arrays of submillimeter bolometers have been realized by this folding method and then stacking subsequent arrays.

The first metallization step is typically the deposition of the bilayer material onto a cleaned substrate (Mo/Au [6] and Mo/Cu [5] deposition parameters have been described elsewhere). We choose Mo-based superconducting bilayers with noble metal toplayers (Cu and Au are currently under investigation) deposited by e-beam or sputtering deposition. The Mo layers have been shown to be highly reproducible and uniform across a wafer and provide long term stability because no intermetallics form at the interface of the two materials. Au provides a corrosion resistant toplayer whereas Cu provides more access to selective etches between the Mo and noble metal layer. Electron-beam Mo is deposited at high temperature (700 C) has shown highly reproducible Tc in thin layers, but the high temperature deposition restricts what processing occurs before the bilayer deposition. Sputtered bilayer Tcs are showing good reproducibility in dedicated deposition systems. After the TES bilayer is wet-etched, liftoff Nb leads are deposited. Areas for wirebonding to the Nb are protected with Al pads to enable superconducting contact without introducing stray resistance into the detector loop. Liftoff Au or Cu bars along the edge of the film are used to protect the bilayer from degradation and promote normal metal boundary conditions for the superconducting sensor element. Metallization to thermalize the frame chip and to integrate on-chip shunt resistors are typically fabricated with a Ti/Au liftoff.

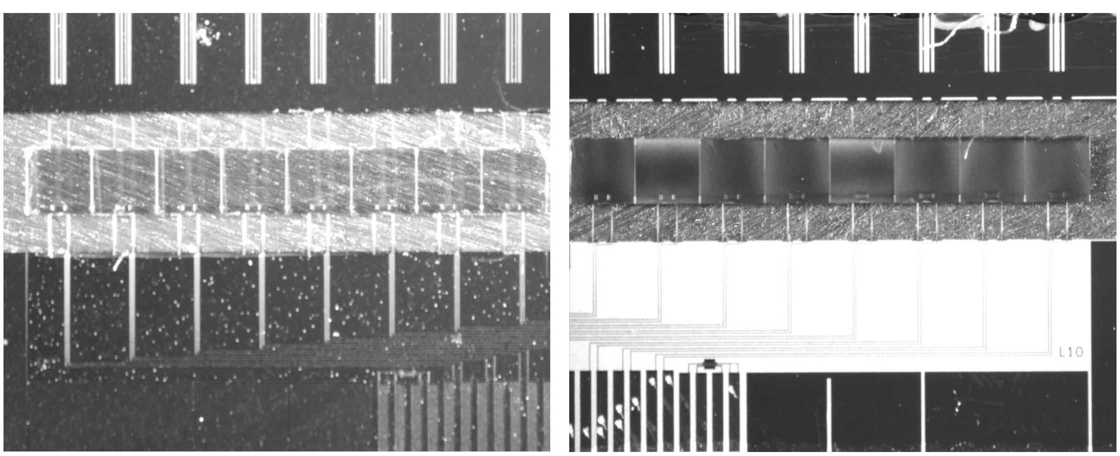

Figure 1 (a) A 1x8 superconducting transition edge sensor bolometer array in which eight 1 mm^2 SiN membranes are connected to the frame chip by .5 micron wide legs. (b) A similar 1x8 array on which a Bi/SiO submillimeter absorber coating has been deposited on the SiN pixels

That a thin metal absorber matching the impedance of free space is an effective submillimeter absorber is well established [e.g., ref. 8]. Choosing the absorber for large area submillimeter pixels and suitable for large format arrays, we considered several factors. Bi films, thermally evaporated from a tungsten wire wrapped alumina crucible at 1 Angstrom/second, feature good reproducibility and suppression of aging effects when passivated. An SiO layer is readily thermally evaporated on top of the fresh Bi layer without breaking vacuum. While these properties can be achieved with alloys such as AuPd or CrSi, their large heat capacity can dominate the device time constant and even lead to excess noise. The vanishing heat capacity of Bi films permits broadband absorption without affecting device parameters. Depositing Bi/SiO on both sides of the membrane mitigates the effects of film stress on the micromachined structure. We are developing these multilayer absorbers instead of single layers to avoid bending focal plane elements out of the plane with film stress. A single layer of 400 Ω/sq Bi was observed to deflect these membranes by up to 60 microns.

ABSORPTION IN BISMUTH

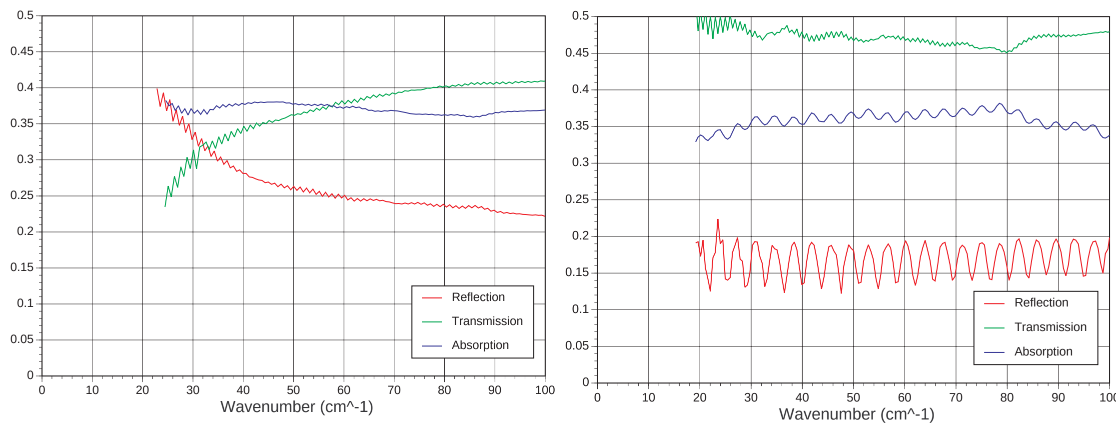

Figure 2(a) The rightside plot shows submillimeter transmission (top curve at right axis) and reflectance (bottom curve at right axis) for a 240 Ohm Bi/SiO bilayer on a 1 micron SiN membrane measured at 4 K. The middle curve is the calculated absorption in the Bi. Note the transmission exhibits a strong frequency dependence across the submillimeter (b) The leftside plot shows submillimeter absorption (top curve) and reflectance (bottom curve) and calculated absorption (middle curve) for a similarly deposited 400 Ohm/Sq Bi/SiO Bilayer. The ripple in the measured reflectance result from a spurious effect of the Si frame intruding on the path of the beam in the FTS.

We characterized several absorber structures with reflectance and transmission measurements taken at a temperature of 4K with a Fourier Transform Spectrometer (FTS). The .5 micron thick SiN is sufficiently thin that submillimeter radiation will treat the films as parallel resistors. The sample resistances (240 Ω/sq for the sample shown on the left side and 400 Ω/sq on the right side) are the 4K 4-terminal Bi resistances measured on witness slides which accompanied the sample during the deposition and added in parallel. As one would expect, transmission is increased and reflectance is decreased by pushing to higher resistance films in the absorber. However, submillimeter absorption is similar (>35 %) with resistance change across the submillimeter band. The more transmissive film is advantageous in a resonant absorption geometry such as the FIBRE instrument, which uses a quarter-wave (λ/4) backshort at 350 microns (30 wavenumbers). The measurements show that broadband absorption with Bi is achieveable. The reflectance on the right hand plot - and hence the absorption – shows a spurious interference effect due to the .4 mm thick silicon frame supporting the membrane.

NOISE SUPPRESSION IN MO-BASED DETECTORS

We have observed excess noise in Mo/Cu and Mo/Au films. The plot on the left is data from a Mo/Au film for which both layers were wet etched. The Mo is observed to undercut slightly from the Au at the edges of the film during the wet etch and a sharp transition to the superconducting state is observed in witness samples and the device. Biased low on the transition, the device exhibits a 1/f knee above 1 Hz and excess noise in band well above the phonon noise limit. The magnitude of this noise varies widely with bias (including some lower noise regions where the midband noise "bump" disappears). This Mo/Au device did not approach the phonon-noise limit at any bias. Similarly etched Mo/Cu films also show excess noise although they approach the phonon noise limit when biased near the top of the transition. We modified the design of the Mo/Cu detectors by lifting off thick Cu bars along the edges of the film. The plot on the right shows data from a Mo/Cu detector with a somewhat higher Tc (~500 mK) The noise biased near the top of the transition is white, phonon-noise limited, and exhibits a 1/f knee of .1 Hz. Biased lower on the transition, some midband noise arises but the 1/f is still very low. Normal metal boundary conditions appear to be significant to device behavior in Mo-based bilayers. The Mo/Au detectors achieved lower noise and better device reproducibility by undercutting the Mo from the edges of the film leaving a Au edge. Submillimeter devices with liftoff Au bars are in production.

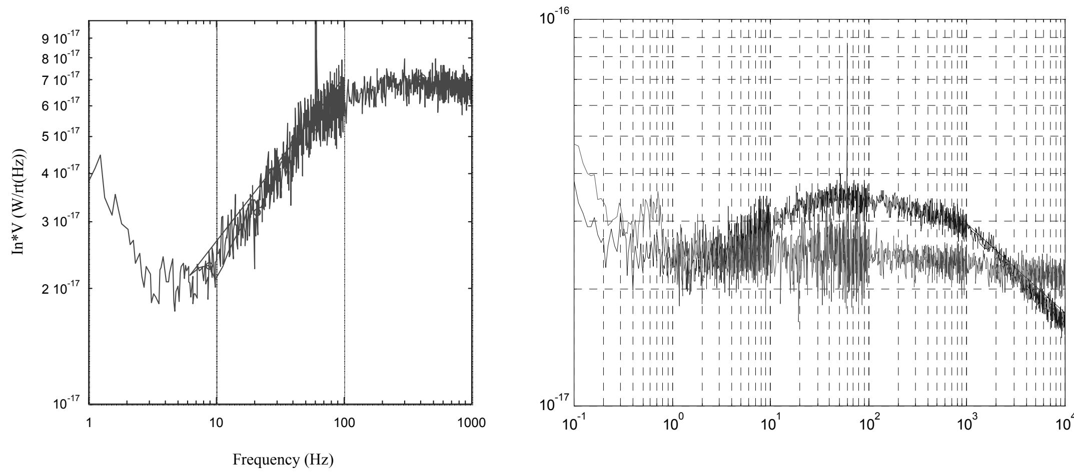

Figure 3. (a) Left side. Measured noise power (Current noise multiplied by bias voltage) in a biased TES consisting of a wet-etched Mo/Au bilayer with a Tc of 440 mK. The device shows strong 1/f and midband noise components which varies with bias and does not reach the phonon noise limit, even in the low noise region (2-20 Hz). (b) Right side. A Mo/Cu device with a Tc of 508 mK shows phonon-noise limited performance in the signal band and SQUID limited 1/f noise. The curve which exhbits no excess noise "bump" midband is biased at 80 % of the transition while the noise "bump" curve is biased at 50% of the transition. Note the 1/f knee changes with current noise in the device so that the lower bias point (higher current noise relative to the SQUID noise floor) shows a lower 1/f knee which corresponds to the SQUID 1/f noise.

REFERENCES

1. K.D. Irwin. "An application of electrothermal feedback for high resolution cryogenic particle detection", Appl. Phys. Lett. **66**, 1998-2000 (1995), A. T. Lee, et. al "A superconducting bolometer with strong electrothermal feedback" Appl. Phys. Lett. **69**, 1801 (1996)
2. J. A. Chervenak, et. al. "Sub-picowatt precision radiometry using sup[erconducting transition edge sensor bolometers", IEEE Trans Appl Supercon. **11**, 593 (2000), D. J. Benford, et. al. Int J. IR MM Wav. **21** (12) 1909-1926 (2000)
3. J. A. Chervenak, et. al. "Superconducting Multiplexer for Arrays of Transition Edge Sensors" Appl Phys. Lett **74**, 4043 (1999), J. G. Staguhn, et. al "TES Detector Noise Limited Readout Using SQUID Multiplexers". Ninth Int Workshop on Low Temp Det., Madison, WI, p. 321 (2001).
4. D. Dowell Proc. Far-IR, Sub-mm & mm Detector Technology Workshop, Monterey, CA, 2002, in press
5. W. Duncan, et.al. "SCUBA-2: Application of LTD Technology" ". Ninth Int Workshop on Low Temp Det., Madison, WI, p. 577 (2001)
6. G. C. Hilton, et. al ."Microfabricated Transition Edge X-ray Detectors", IEEE Trans Appl. Supercon. **11**, 739 (2001).
7. Tralashawala, Nucl Instr. and Meth A **444**, 188-191 (1999)
8. J. Clarke, et. al. J. Appl. Phys. **48**, 4865 (1977).